Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-11 (2016) 001–007

Diesel Engine Emission Model Transient Cycle Validation

Dhinesh V Velmurugan * **Markus Grahn** * **Tomas McKelvey** **

* *Volvo Car Corporation, Gothenburg, Sweden. (e-mail: dhinesh.velmurugan@volvocars.com, markus.grahn@volvocars.com).*
** *Department of Signals and Systems, Chalmers University of Technology (e-mail: tomas.mckelvey@chalmers.se)*

Abstract: A control intended data driven B-spline model for NO_x and soot emitted was developed and validated for the 5-cylinder, 2.4-litre Volvo passenger car diesel engine in earlier work. This work extends on the same methodology with some improvements on the model structure for more intuitive calibration and is also developed for the new generation 4-cylinder, 2-litre Volvo passenger car diesel engine. The earlier model was validated using steady state engine measurements and proposed that the model would hold good for transient engine operation. The hypothesis formulated is that a transient engine emission model can be envisioned as a sequence of multi-step steady state engine operation points with minor deviations from the nominal engine operating conditions. The theory is supported by the literature that provides more insight into the transient operation. This idea is carried out in the current work using engine test cell measurements validated for a NEDC as well as a normal road drive cycle that depicts a more transient driving behaviour in comparison to the standard emission driving cycles. Nearly 4600 engine operating points with steady state measurement including nominal and deviant conditions have been used in the development of the model. The ability of the data driven approach to mimic the engine emission generation characteristics during the engine transient operation is analysed and its superior performance in comparison to the Nominal model and the Regression model is demonstrated.

Keywords: Diesel Engines, Engine modelling, Splines, Automotive Emissions, Transient Analysis

1. INTRODUCTION

Harmful effects of Nitrogen Oxides and Particulate Matter emitted from automobile sources are well established in several studies. The ill effects of both short term and long term exposure to diesel exhaust in all intensities could induce respiratory complications and lifetime cancer risk among other hazards. The environmental effects of diesel exhaust such as acid rain, smog and the much debated climate change impose several concerns for the future of human well-being forcing actions by the respective regional transport bodies such as the European Union, US Environment Protection Agency etc., in establishing diesel exhaust emission norms and enforcing stricter norms with the passage of time and advancement of technology. See US EPA. (2002).

1.1 Emission Norms

The path taken by exhaust emission regulatory agencies for the passenger car segment (light duty diesel engine applications) until the recent past (eg. from Euro 1 to Euro 6b) have been more of a reduction in the limits of permitted NO_x and Diesel soot for a specific driving cycle. The representative cycle has not changed significantly to adapt to technological changes over decades. The steps in emission norm updates have led to the introduction of emission reducing technologies such as Diesel Oxidation Catalyst, Cooled EGR, Diesel Particulate Filter and Lean NO_x Trap. Statistical evidence from on road emission tests have recorded dramatic increase in exhaust emissions widening the gap between perceived realities and expected emission reduction and thus non-attainment of emission goals envisioned. This has led to the framing of upcoming emission norms which will include on road emission monitoring and thus be based on real driving conditions with enhanced coverage of engine operating conditions. See CARS (2020).

In order to comply with real drive emission limits, significant improvements in Engine and After-treatment design have to be undertaken to bring emission compliance in areas that were once considered out of bounds. The impacts on the diesel engine calibration are on both the coverage area of Speed - Load of the engine as well as the operating conditions such as handling transient behaviour, ambient conditions, and driver- disturbances. The changes imparted would lead to enhanced challenges on the control of the transient characteristics of the engine.

1.2 Modelling perspective: Cost-Accuracy trade-off

Emission formation in engines is a complex non-linear process that is dependant on a wide range of operating conditions. The established formation mechanisms used in

10.1016/j.ifacol.2016.08.001

simulations today, already involving complex calculations using powerful computers might be able to model the diesel emissions after considerable effort. However this is still a simplified model considering only a few combustion parameters and needs to be adapted to the specific engine being dealt with. These methods based on first principles are extremely slow in comparison to real time applications and are intended for research phases. A more hybrid methodology using simplifications of the first principles and calibrated using real measurement data is used in conceptual phases. Considering the computational power and the response time requirement in the Engine Management System (EMS), it is not possible to implement first principles based models in production systems and thus makes the case for data driven model implementation. Moreover, estimation of emissions in absolute values have been easier with data driven models in comparison. From a user point of view, data driven methods offer far better tuning and calibration opportunities.

1.3 NO_x and Soot modelling

NO_x and soot predictability is a highly effective tool for a well-integrated supervisory control of the engine and after treatment system. The emission models in the EMS needs to be fast and accurate to trigger after-treatment control measures. The accuracy of the emission models will be vital for the further development of closed loop emission controls. The simplification processes that the model undergoes to be able to be faster involve significant deterioration in accuracy of the emission estimation. Therefore it is a combined goal of increasing the accuracy with minimal increase in model complexity. This is being attained with the help of advanced mathematical methods that have shown promising results. The use of Gaussian methods, Neural networks, Regression models, Bayesian techniques and Splines have been experimented by the researchers in this field. While most have documented performance on Steady state engine operating conditions, few have ventured into their transient response. Even as these transient behaviour are examined they are mostly limited to the standard emission test cycles. See Berger et al. (2011) Brahma et al (2009) Grahn M et al (2012a).

2. EMISSION FORMATION IN TRANSIENT ENGINE OPERATION

A transient engine operation occurs due to change in requested engine speed or load. Engine speed dynamics result in altered time per diesel cycle leading to disturbances in the combustion chamber and the air entrapment until the attainment of an assumed steady state. Dynamics in engine load alters the air-fuel ratio that affect the power and heat release resulting in thermal fluctuations compared to steady state operation. See Constantine and Evangelos (2009), Heywood (1988) for more theory.

2.1 Soot and NO_x formation

Soot formation during transient engine conditions deviates from steady state operation because the boosting system dynamics are not as fast as the fuelling rate changes. The resultant soot emitted in the diesel exhaust is influenced by the obtained air - fuel mixture. NO_x formation is strongly dependant on in cylinder temperature which in turn depends on Oxygen concentration and combustion duration. During an engine transient, change of load leads to increased fuelling and smoke control measures such as EGR starvation then may lead to a NO_x spike.

In order to estimate the emission components during the engine transient operation, these causes should be suitably captured by the underlying model.

3. B-SPLINE MODEL FOR NOx AND SOOT MODELLING

3.1 Background

The work carried out with respect to NO_x and soot modelling using first order B-Splines utilising their linear equivalence has been established and documented in the early works in Grahn M et al (2012b). A globally optimised, smoothened, regressive parameter based, B-Spline function applied to perform model calibration using data fitting method was established and verified in static engine operating conditions for a 5 cylinder Volvo diesel engine. The model is summarised as

$$log\left(\frac{\hat{\alpha}}{x_1 \cdot x_2}\right) = f_0(x_1, x_2) + \sum_{i=1}^{3} z_i \cdot f_i(x_1, x_2) \quad (1)$$

where $\hat{\alpha}$ denotes the predicted Engine out soot or NO_x, x_1 and x_2 are the input signals Engine Speed and Fuel Injected quantity respectively, z_i are other emission affecting input signals to the model, $f_0(x_1, x_2)$ and $f_i(x_1, x_2)$ are model parameters represented by two dimensional linear interpolation maps.

This paper focuses on simulating such a model developed for a real world driving condition applied to the new Volvo Diesel engine, specifications of which are listed below

Table 1. Engine Specification

Cylinder pitch(mm)	91
Bore(mm)	82
Stroke(mm)	93.2
No. of cylinders	4
Swept Volume (l)	1.969
Compression ratio	15.8

3.2 Desired model properties

The development phase of a diesel engine normally undergoes years of calibration updates for efficient engine control. It is the motive of this work to capture the effect of such changes without requiring to acquire new data from the engine repeatedly with each calibration. Thus given no hardware changes on the engine, the model would be representative of the engine irrespective of the calibration change since the dynamics of the emission formation are captured by operating the engine with the permissible degrees of freedom.

The models should be comprehensible to the calibration engineer and be intuitive as to how the factors in the calibration affect the predicted quantities. The objective is a model of the diesel engine soot and NO_x emissions that